METEOROLOGY

Are there trends in hurricane destruction?

Arising from: K. Emanuel *Nature* 436, 686–688 (2005)

Since the record impact of Hurricane Katrina, attention has focused on understanding trends in hurricanes and their destructive potential. Emanuel[1] reports a marked increase in the potential destructiveness of hurricanes based on identification of a trend in an accumulated annual index of power dissipation in the North Atlantic and western North Pacific since the 1970s. If hurricanes are indeed becoming more destructive over time, then this trend should manifest itself in more destruction. However, my analysis of a long-term data set of hurricane losses in the United States shows no upward trend once the data are normalized to remove the effects of societal changes.

Historical hurricane losses can be adjusted to a base year's values through adjustments related to inflation, population and wealth[2]. For at least three reasons, this data set is appropriate for identifying long-term climate signals. First, a long-term record of flood damage (collected in a similar way to and by the same agency as the hurricane data) is of sufficient quality to identify long-term trends[3]. Second, a methodology[2] developed in 1998 produces results that are consistent with the results of catastrophe models used by the insurance industry to assess hurricane losses[4]. Third, and most crucially, the data set contains climate signals, such as that of the El Niño–Southern Oscillation, which has a well established climatological relationship with interannual hurricane behaviour (see refs 5, 6, for example).

Specifically, an index of sea-surface-temperature anomalies of the Niño 3.4 region of the central Pacific in August, September and October is highly correlated with observed normalized damages in the same year[5]. The observed intensity change[7] in Atlantic basin hurricanes between El Niño and La Niña events is of similar magnitude to the changes in annual accumulated power-dissipation index identified by Emanuel[1]; the ability to identify the signal of the former suggests therefore that the normalized damage database is of sufficient size and quality to identify climate signals of the magnitude discussed by Emanuel.

A data set of hurricane losses (focusing on direct damages related to wind, and generally excluding rain-caused flood damage) for individual storms[6] extended to 2004, which includes only those storms causing damage, shows no upward trend. For example, take the 86 storms causing at least US$1 billion in normalized damages, which removes a bias caused by small storms resulting in no damage in the early twentieth century (that is, not subjected to normalization). There is an average per-storm loss in 1900–50 for 40 storms (0.78 events per year) of $9.3 billion, and an average per-storm loss in 1951–2004 for 46 storms (0.85 events per year) of $7.0 billion; this difference is not statistically significant. Adding Hurricane Katrina to this data set, even at the largest loss figures currently suggested, would not change the interpretation of these results.

These loss data indicate two possibilities with respect to Emanuel's analysis[1]: if the power-dissipation index metric is an accurate indicator of hurricane destructiveness, then the trend identified by Emanuel could be an artefact of the data and/or methods; alternatively, the trend he identifies is an accurate reflection of trends in the real-world characteristics of storms, but the power-dissipation index is a weak indicator of hurricane destructiveness — which would call for the identification of climate metrics more directly associated with societal outcomes. In any case, it is misleading to characterize Emanuel's results as indicating an increase in "destructiveness" or as an indication of future increases in destruction resulting from changes in the power-dissipation index.

The bottom line is that, with no long-term trend identified in normalized hurricane damage over the twentieth century (in the United States or elsewhere; see ref. 8, for example), it is exceedingly unlikely that scientists will identify large changes in historical storm behaviour that have significant societal implications. Looking to the future, Emanuel[1] provides no evidence to alter the conclusion that changes in society will continue to have a much larger effect than changes in climate on the escalating damage resulting from tropical cyclones[9].

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METEOROLOGY

Hurricanes and global warming

Arising from: K. Emanuel *Nature* 436, 686–688 (2005)

Anthropogenic climate change has the potential for slightly increasing the intensity of tropical cyclones through warming of sea surface temperatures[1]. Emanuel[2] has shown a striking and surprising association between sea surface temperatures and destructiveness by tropical cyclones in the Atlantic and western North Pacific basins. However, I question his analysis on the following grounds: it does not properly represent the observations described; the use of his Atlantic bias-removal scheme may not be warranted; and further investigation of a substantially longer time series for tropical cyclones affecting the continental United States does not show a tendency for increasing destructiveness. These factors indicate that instead of "unprecedented" tropical cyclone activity having occurred in recent years, hurricane intensity was equal or even greater during the last active period in the mid-twentieth century.

My first concern is that Emanuel's figures[2] do not match their description: his Figs 1–3 aim to present smoothed power-dissipation index (PDI) time series with two passes of a 1-2-1 filter, but the end-points — which are crucial to his conclusions — instead retain data unaltered by the smoothing; this is important because the last data point plotted in Emanuel's Fig. 1 is far larger than any other portion of the time series. Even after adding last year's busy hurricane season into the analysis and then properly using the filter, as described, the crucial end-point of the smoothed time series no longer jumps up dramatically in the last couple of years (Fig. 1a). About one-third of the increase in Atlantic PDI in Emanuel's graph for the past ten years is incorrect owing to inappropriate plotting of the data, even if the active 2004 season is incorporated.

A second concern is the bias-removal scheme used to alter the data for the Atlantic for 1949–69. Emanuel can demonstrate "unprecedented" activity in the past ten years only by markedly reducing the tropical-cyclone winds for the first two decades of the time series. He attempts to use a bias-removal scheme[3] that recommends reduction of the tropical-cyclone winds by 2.5–5.0 m s^{-1} for the 1940s–60s because of an inconsistency in the pressure–wind relationship during those years compared with subsequent (and presumably more accurate) data. However, the function used by Emanuel to reduce the winds in the earlier period goes well beyond this recommendation, as the bias removal used continued to increase with increasing wind intensity and reached a reduction of as much as 12.2 m s^{-1} for the strongest hurricane in the 1949–69 original data set.

In major hurricanes, winds are substantially stronger at the ocean's surface[4–7] than was previously realized, so it is no longer clear that Atlantic tropical cyclones of the 1940s–60s call for a sizeable systematic reduction in their wind speeds. It is now understood to be physically reasonable that the intensity of hurricanes in the 1970s through to the early 1990s was underestimated, rather than the 1940s and 1960s being overestimated[8]. To examine changes in intensity over time, it is therefore better to use the original hurricane database than to apply a general adjustment to the data in an attempt to make it homogenous.

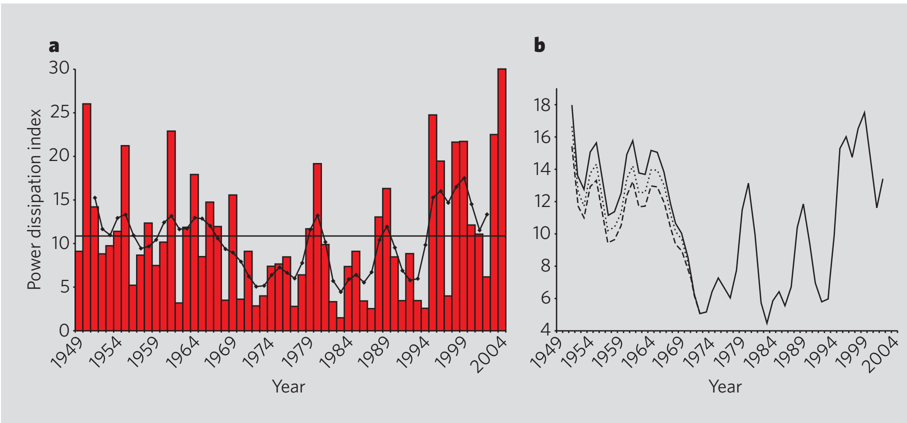

Figure 1 | Derivation of Atlantic power-dissipation index (PDI). **a**, Emanuel's bias-correction version[2] of PDI for the North Atlantic tropical cyclones for 1949–2004. PDI takes into account frequency, duration and intensity of tropical cyclones by cubing the winds during the lifetime of the systems while they are of at least tropical-storm force (18 m s^{-1}) and summing them up for the year. Values shown are multiplied by 10^{-6} in units of m^3 s^{-3}. Horizontal line, time-series mean of 10.8; black curve, data after smoothing with two passes of a 1-2-1 filter. **b**, Three versions of the smoothed PDI for the North Atlantic using: dashed line, Emanuel's applied bias-removal scheme; dotted line, 1993 version[3] of the bias-removal scheme; solid line, original hurricane database. All three versions are identical from 1970 onwards.

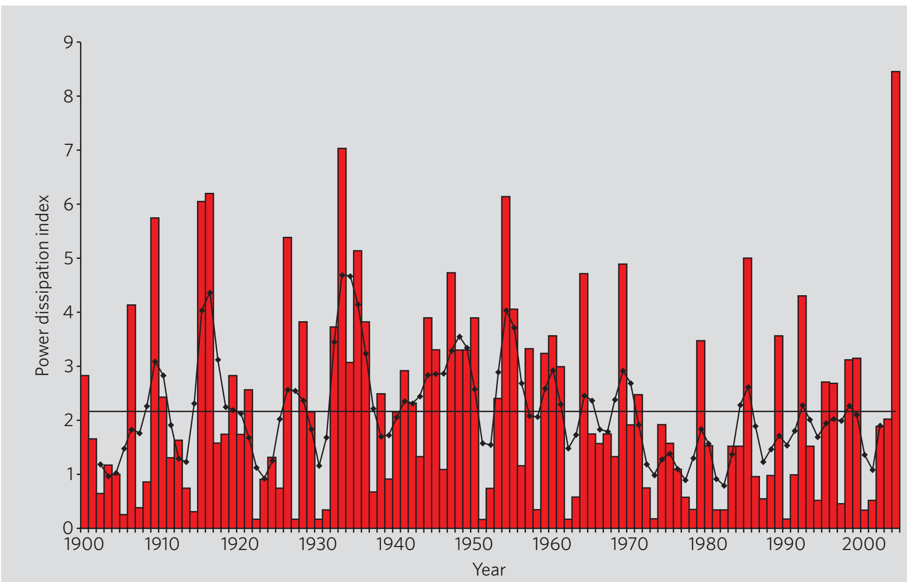

Figure 2 | The continental United States PDI at the time of impact for the reliable-period record of 1900–2004. This is computed from the best estimate of the peak sustained (1 min) surface (10 m) winds to have affected the US coastline for all tropical storms, subtropical storms and hurricanes causing at least gale-force (18 m s^{-1}) winds. Values shown are multiplied by 10^{-5} in units of m^3 s^{-3}. Horizontal line, time-series mean; black curve, data after smoothing with two passes of a 1-2-1 filter. For the continental US coast, the year 1900 roughly marks the start of a complete database. (Before that, portions of Florida, Louisiana and Texas were too sparsely settled to ensure adequate monitoring of all tropical cyclones, particularly those that were small but intense like 2004's hurricane Charley.) The year 2004 stands out as the busiest from the twentieth century to the beginning of the twenty-first century, with 20% more PDI than the second most-active year in 1933. (However, 2004's US PDI value is slightly less than that estimated to have occurred in 1886, as at least seven landfalling hurricanes struck that season, the busiest on record since 1851.)

Figure 1b shows Emanuel's bias-removed smoothed curve and the substantially larger PDI values in the original hurricane data set; the latter indicates that amplitudes for 1949–69 are comparable to those for the most recent decade. This is consistent with earlier work[9,10], emphasizing the large multidecadal oscillations in activity. It is also likely that values of PDI from the 1940s to the mid-1960s are substantially undercounted owing to the lack of routine aircraft reconnaissance and geostationary satellite monitoring of tropical cyclones far from land.

A third concern is that it is difficult to separate out any anthropogenic signal from the substantial natural multidecadal oscillations with a relatively short record of tropical-cyclone activity. One way to extend the PDI analysis back to include several additional decades of reliable records is to examine only those tropical cyclones that made landfall along populated coastlines[11,12]. Figure 2 shows that tropical-cyclone activity in the United States was generally extremely busy between the 1930s and 1960s, but fell below average between the 1970s and early 1990s. Despite the extreme value for 2004, the most recent decade has a PDI that is near-average for the United States, rather than showing an increase in the overall number and intensity of hurricane strikes.

Despite these problems, Emanuel's study illustrates the pressing need for a completion of the storm-by-storm reanalysis of the Atlantic hurricane database[8,11], which will provide a more homogeneous time series of tropical-cyclone intensities and so avoid the application of arbitrary bias-removal schemes. But, on the basis of the evidence I present here, claims to connect Atlantic hurricanes with global warming are premature. The Atlantic hurricane basin is currently seeing enhanced, rather than "unprecedented", storminess that is comparable to, or even less active than, that seen in earlier busy cycles of activity.

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METEOROLOGY

Emanuel replies

Replying to: R. A. Pielke *Nature* 438, doi:10.1038/nature04426 (2005) and C. W. Landsea *Nature* 438, doi:10.1038/nature04477 (2005)

In my original Article[1], I showed that there has been a significant upward trend in a measure of tropical-cyclone power dissipation over the past 30 years[1]. It is important to note that this measure is integrated over the life of the storm, and that the upward increase is evident in all major ocean basins prone to tropical cyclones. However, Pielke[2] finds no discernible trend in hurricane damage in the United States after correction for inflation and demographic trends, and Landsea[3] finds no trend in US landfall-based hurricane power dissipation back to the turn of the last century.

Pielke suggests[2] that this apparent disparity could be explained if the power-dissipation trend I find is an artefact of the data and/or analysis methods, or if the trend is accurate but not a good predictor of damage. As this trend is large and universal — having about the same value in all the major ocean basins, despite different measurement techniques — and as it is well correlated with sea surface temperature (SST), which is relatively well measured, I stand by my conclusions about the trends in tropical-cyclone power dissipation.

I cannot discount the second of Pielke's conjectures, but the reason for the disparity may be more prosaic. Although Atlantic hurricanes do most of their destruction within 6–12 hours after landfall, they last for an average of 180 hours; moreover, only a fraction of hurricanes ever affect the US coastline. This means that the power-dissipation index (PDI) I used, which is accumulated over all storms and over their entire lives, contains about 100 times more data than an index related to wind speeds of hurricanes at landfall. There is large variability in wind speed over the life of each storm and large storm-to-storm random variability: detecting a temporal trend in the presence of this variability requires separation of the signal from the noise. With 100 times more data, my index has a signal-to-noise ratio that is ten times that of an index based on landfalling wind speeds. It is therefore possible that the real trend is detectable in the power dissipation but not in landfalling statistics. A simple calculation based on the observed root-mean-square variability of hurricane activity indicates that this is indeed the case, and probably explains why Pielke[2] and Landsea[3] find no trends in US landfall data.

Pielke argues that because El Niño can be detected in hurricane damage, a trend related to PDI should also be evident, if it exists. But the detectability of an El Niño signal in US hurricane damage is marginal, explaining only 3–4% of the variance[4]. Tropical Atlantic SST explains far more of the variance of both total Atlantic tropical-cyclone numbers and average tropical-cyclone intensity than does El Niño; but curiously, SST is even less correlated with a measure of US landfalling storm activity than El Niño. This probably once again reflects the difficulty of detecting trends in sparse time series in which the amplitude of random fluctuations is large compared with the signal.

The failure of any trend in landfall statistics to emerge from the noise is itself significant, and supports Pielke's view that demographic trends will be more important than climate change in coming years. But this is a short-term and US-centric view. When global tropical-cyclone activity is considered, and not just the 12% that occurs in the Atlantic region, a trend in landfalling intensity is already apparent; even in the Atlantic the signal, if it exists, is similar to the PDI trend, and if it continues should emerge from the noise in a few decades.

Landsea[3] starts by saying that increasing SST has the potential for "slightly" increasing the intensity of tropical cyclones. But, as I discussed[1], the existing theory and modelling[5] on which this assertion is based suggest that the predicted ~2 °C increase in tropical SST would increase wind speeds by 10% and, accounting for increased storm lifetime, increase power dissipation by 40–50%. This is hardly slight. The existing theory and modelling work[5] are limited, however, in that they do not account for changes in environmental conditions, such as wind shear, and so only provide a loose guide as to what to expect.

Landsea correctly points out that in applying a smoothing to the time series, I neglected to drop the end-points of the series, so that these end-points remain unsmoothed. This has the effect of exaggerating the recent upswing in Atlantic activity. However, by chance it had little effect on the western Pacific time series, which entails about three times as many events. As it happens, including the 2004 and 2005 Atlantic storms and correctly dropping the end-points restores much of the recent upswing evident in my original Fig. 1 and leaves the western Pacific series, correctly truncated to 2003, virtually unchanged. Moreover, this error has comparatively little effect on the high correlation between PDI and SST that I reported[1].

In correcting for biases in the original Atlantic tropical-cyclone data, I relied on a bias correction applied by Landsea[6], presented as a table. I had fitted a polynomial to that correction, as I felt that a continuous rather than discrete correction was more defensible. Landsea believes that this had the effect of overcorrecting the most intense storms in the pre-1970 record, and I accept his revision to my analysis (Fig. 1b of ref. 3).

The Atlantic hurricane-intensity record by itself is not long enough to infer any connection between hurricanes and either global warming or multi-decadal cycles, but the high correlation between hurricane activity and tropical SST is remarkable (and largely unaffected by the corrections discussed), and the SST record is long enough to show the influence of global warming. To detect correlations with hurricane activity, tropical cyclones in the North Atlantic can be counted, assuming that detection of the presence of a storm by ships and islands is reliable (although intensity estimation is dubious before the mid-1940s). This count is highly correlated with both tropical Atlantic SST and Northern Hemispheric mean surface temperature through the entire record, casting doubt on whether the recent multidecadal variability in tropical SST and hurricane activity is due purely to natural causes, as Landsea implies[3].

I maintain that current levels of tropical storminess are unprecedented in the historical record and that a global-warming signal is now emerging in records of hurricane activity. This is especially evident when one looks at global activity and not just the 12% of storms that occur in the Atlantic. But I agree that there is a pressing need for a storm-by-storm reanalysis of tropical cyclones, not only in the North Atlantic, but also in the western North Pacific, where aircraft reconnaissance records also extend back to the 1940s.

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